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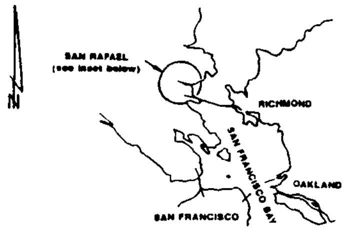
TECHNICAL REPORT HL-89-24

SEDIMENTATION ANALYSIS OF THE PROPOSED SAN RAFAEL CANAL TIDAL BARRIER SAN RAFAEL, CALIFORNIA



VICINITY MAP

AD-A217 213

by

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DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

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A tidal barrier is proposed as a control measure to prevent tidal flooding in the San Rafael Canal, San Rafael, CA. This study investigated at a feasibility level the interaction between sedimentation and the tidal barrier. For this study, a brief site trip with limited sampling of suspended sediments and bottom cores was conducted, historical dredging records for San Rafael Canal were analyzed, historical suspended sediment data from nearby San Francisco Bay were obtained, sediment characteristics for erodibility from prior flume tests conducted on San Francisco Bay bottom sediments were obtained, and freshwater inflow exceedance interval hydrographs were obtained for the 2-, 10-, 50-, 100-, and 500-year events. Finally a zero-dimensional numerical model was developed to evaluate erosion and deposition for the 1989 astronomical tides at two alternative tidal barrier locations. In the vicinity of San Rafael Canal where the tidal barrier

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would be located, tidal sediment movement appears to predominate rather than riverine sediment transport.

Results of the numerical model substantiated by the dredging records, indicated that the existing San Rafael Canal has a net depositional pattern. The increased velocities from the reduced cross section of the tidal barrier changed the numerical results to predict net erosion tendencies at both tidal barrier sites evaluated. These results indicate that the tidal barrier concrete apron will be kept relatively free of deposits that might otherwise interfere with operation of the barrier. The net erosion also indicates that erosion protection may be necessary around the tidal barrier apron. Freshwater inflow flood events can result in high velocities around the barrier with substantial capacity to erode. Except in the immediate vicinity of the tidal barrier, the San Rafael Canal will not be impacted by the proposed project.

PREFACE

The investigation at a feasibility study level of the interaction of sedimentation processes and the proposed tidal barrier in San Rafael Canal as documented in this report was performed for the US Army Engineer District, San Francisco.

The study was conducted in the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES) during the period April 1989 to June 1989 under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL; R. A. Sager, Assistant Chief, HL; W. H. McAnally, Jr., Chief, Estuaries Division; and J. V. Letter, Jr., Chief, Estuarine Simulation Branch.

This work was performed and the report prepared by Mr. L. M. Hauck, Estuarine Simulation Branch. This report was edited by Mrs. M. C. Gay, Information Technology Laboratory, WES. Messrs. W. J. Brick and A. Mathiesen of the San Francisco District organized and assisted on the data collection field trip, and Mr. Brick was liaison for the San Francisco District. The efforts of the City of San Rafael, including the use of their police boat and pilot for the data collection field trip, are acknowledged.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US Statute)	1.6093	kilometres
square miles	2.589998	square kilometres
square yards	0.836127	square metres

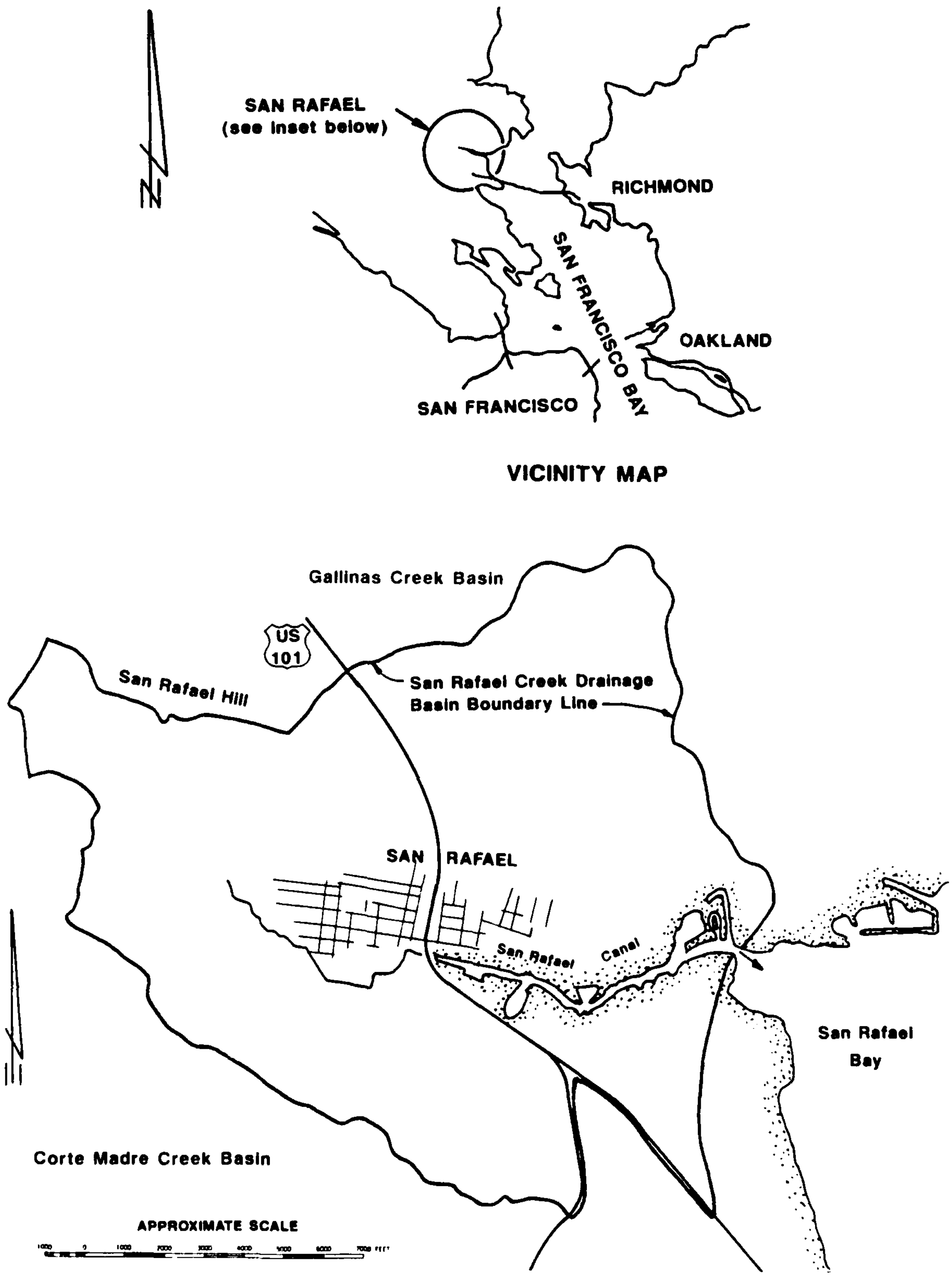

Figure 1. Vicinity map and drainage basin boundaries

SEDIMENTATION ANALYSIS OF THE PROPOSED SAN RAFAEL CANAL TIDAL BARRIER

PART I: INTRODUCTION

Background

1. Located in central Marin County approximately 17 miles* north of the city of San Francisco, CA, the San Rafael Creek basin encompasses a drainage area of 7.1 square miles (Figure 1). The basin, which is predominately urbanized, is bounded on the north by the Gallinas Creek basin, to the east by San Rafael Bay, to the south by the Corte Madera Creek basin, and to the west by the coastal mountain range. San Rafael Creek extends 4.5 miles from San Rafael Bay to the basin ridge line of San Rafael Hill. The upstream reach is steep and narrow, while the downstream reach of approximately 1.5 miles length is wide and of nearly uniform depth. This downstream reach, referred to as the San Rafael Canal, is a US Army Corps of Engineers navigation project with a maintained depth of 6 ft below mean lower low water (mllw) and a project width of 60 ft.

2. The first interim phase of the Marin County Shoreline Study investigated tidal and riverine flooding problems in the city of San Rafael in the vicinity of the San Rafael Canal. During the reconnaissance study, two primary alternatives emerged: (a) a floodwall-levee system to keep tidal and freshwater floodwaters out of damage-prone areas, and (b) a tidal barrier with a tieback levee system constructed across a lower portion of the canal to prevent extreme high tides from entering damage-prone areas. A pumping plant would be constructed as part of the tidal barrier alternative to control fluvial runoff when the barrier is closed. The tidal barrier would be closed only at those times when an unusually high predicted astronomical tide coincided with exceptional meteorological conditions, such as low barometric pressure, long-period surge, and/or high winds. Closure of the tide barrier is expected to be necessary for only a few occasions each year.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

Purpose

3. The purpose of this investigation was to determine at the level of a feasibility study the interaction of sedimentation and the tidal barrier alternative in San Rafael Canal. In particular, the following objectives were to be considered:

a. Evaluate the effects of the proposed tidal barrier on San Rafael Canal velocities, sediment concentrations, deposition, and erosion.

b. Evaluate the effects of sediment deposition and erosion patterns on the operation of the tidal barrier.

Attainment of these objectives was constrained by a requirement to report findings to the US Army Engineer District, San Francisco, by 7 July 1989.

Approach

4. The approach used in this feasibility-level investigation was to use available data and to apply accepted engineering principles and theories concerning hydraulics and sedimentation to these data to evaluate sedimentation and erosion potential in the San Rafael Canal with particular emphasis on the proposed tidal barrier locations. The gathering of available data included measurements obtained in San Francisco Bay by the US Geological Survey (USGS) and data from studies sponsored by the San Francisco District on the Alcatraz Island disposal site in San Francisco Bay.

5. A simple zero-dimensional numerical model, explained in paragraph 23 and Appendix A, was developed to use these data. With available bathymetric and astronomical tide predictions, the numerical model was employed to predict erosion and deposition at the proposed tidal barrier. Two possible barrier locations were investigated, and conditions with and without the barrier were determined from the model. Hydraulic head loss was estimated to determine any changes to tidal range in the San Rafael Canal.

PART II: DATA ANALYSIS

6. Available historical data were used as much as possible for this investigation. Total suspended material (TSM) concentrations for the project area were estimated from historical data obtained by the USGS (Smith, Herndon, and Harmon 1979 and Schemel*) in the West Richmond Channel off Point San Pablo and by the US Army Engineer Waterways Experiment Station (WES) (Teeter**) near the Richmond Bridge in September 1988. Information from laboratory erosion testing of San Francisco Bay sediments from a study of San Francisco Bay-Alcatraz Disposal Site erodibility (Teeter 1987) was used to characterize the bottom sediments in the San Rafael Canal. Additional information provided by the San Francisco District included dredging records, predredging and post-dredging surveys in the canal, maps of the canal, estimated hydrographs for the 10-, 50-, 100-, and 500-year exceedance interval basin rainfalls, and preliminary tidal barrier design. All these data were supplemented by a 1-day site visit during which limited sediment sampling was performed.

Site Visit

7. On 16 May 1989, San Francisco District and WES personnel conducted a site visit of the San Rafael Canal. During the site visit, reconnaissance of the San Rafael Canal was undertaken and limited water samples and sediment core samples were collected. The reconnaissance took place in late morning, which happened to coincide with high-water slack. A total of five surface water samples were taken and analyzed for TSM concentration. The four samples taken along the length of the San Rafael Canal ranged in concentration from 5 to 12 mg/ℓ with a mean value of 8 mg/ℓ, and the single sample from the San Rafael Channel in San Rafael Bay had a measured TSM concentration of 41 mg/ℓ.

8. Two 18-in. sediment core samples were taken at the two alternative proposed sites at midchannel. Both cores were very similar; each was a firm, cohesive type sediment that varied in color from brown at the surface to nearly black at the 18-in. depth. A portion of each core from the near surface and the 18-in. depth was saved for laboratory analysis. Laboratory

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* Personal Communication from L. Schemel, 1988, USGS, Menlo Park, CA.
** Personal Communication from A. Teeter, 1988, WES, Vicksburg, MS.

results indicated that over 80 percent of each sample passed through a No. 200 sieve, which confirmed the visual observation of a cohesive type sediment with a high clay-silt content. The darker bottom sample contained approximately 10 percent organic material, while the surface sample contained limited organics. Fine sands composed approximately 10 percent of all samples. The bulk wet density (BWD) of the two surface samples averaged 1.32 g/cm^3. The deeper sample had a BWD of 1.38 g/cm^3, which indicated the expected slight density increase with depth due to sediment overburden and consolidation.

Historical Data Analysis

9. Available historical data were obtained to estimate TSM concentrations in the San Rafael Bay-San Rafael Canal system. While no known data existed for either San Rafael Bay or San Rafael Canal, the USGS obtained near-surface TSM measurements in the 1970's and early 1980's in the deep ship channel off Point San Pablo (Smith, Herndon, and Harmon 1979 and Schemel*). These data were analyzed and determined to have a mean TSM value of 23 mg/ℓ with a range of 5 to 133 mg/ℓ. TSM data obtained by WES** during an intensive survey on 7-8 September 1988 included hourly samples at three stations along the Richmond Bridge taken at three to five depths for 25 hours (one lunar day). The depth- and time-averaged TSM concentration for the three stations together was 40 mg/ℓ with a range of measurements from 8 to 267 mg/ℓ. The lower concentrations were typically measured from surface samples, while the higher concentrations were measured in the near-bottom samples. The average surface TSM value was 25 mg/ℓ.

10. The limited existing TSM data indicate an average TSM concentration of 20 to 40 mg/ℓ, though wide variations were observed. The TSM values for waters in San Rafael Bay that enter San Rafael Canal on the flood tide are expected to fluctuate at least as much as these data due to the shallow depths throughout the bay. It is an often-observed phenomenon that the frequent strong winds of the area will cause sufficient wave action to resuspend sediment in the shallow bays and turn the water a chocolate color.

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* Op. cit.

** Teeter, Personal Communication, op. cit.

Sediment Characteristics and Erodibility Analysis

11. Important information to this investigation were the erodibility and related characteristics of sediments in the San Rafael Canal. Because these site-specific data were not available, the findings of the University of Florida flume studies on San Francisco Bay muds, as reported in Teeter (1987), were used. These erodibility flume studies were conducted on mud samples from Larkspur Channel, Richmond Longwharf manuevering area, and Southampton Shoal Channel. These mud samples were from sites near the present study site and therefore likely to be representative of bottom sediments in the San Rafael Canal.

12. Important information for cohesive sediments obtained from Teeter (1987) included the bed shear stress below which deposition occurs τ_d, the bed shear above which erosion occurs τ_e, and the erosion rate constant M. These parameters are used in equations to describe deposition rates and erosion rates for cohesive (clay) sediments, which is the predominant material found in the estuarine environment and typical of the bottom sediments observed in the lower San Rafael Canal. Based upon the findings in Teeter (1987), the following empirical relationships for bay muds were reported:

$$\tau_e = 1.04(BWD - 1) \qquad (1)$$

$$M = 0.000177 \exp(-2.33\tau_e) \qquad (2)$$

for τ_e given in N/sq m, BWD in g/cu cm, and M in kg/sq m/sec. These parameters are used to describe particle erosion of a cohesive sediment in the Ariathurai-Parthenaides equation given by Ariathurai, MacArthur, and Krone (1977) as

$$E = M\left(\frac{\tau}{\tau_e} - 1\right), \quad \tau > \tau_e \qquad (3)$$

where

E = erosion rate, kg/sq m/sec

τ = bed shear stress, N/sq m

The Manning's shear stress equation was used to determine τ , which gives

$$\tau = \frac{\rho g n^2}{h^{1/3}} U^2 \qquad (4)$$

where

ρ = water density, kg/cu m

g = acceleration of gravity, m/sec^2

n = Manning's bottom roughness coefficient

h = water depth, m

U = vertically averaged current speed, m/sec

13. For depositional conditions, the equation of Krone (1962) was used:

$$S = V_s C \left(1 - \frac{\tau}{\tau_d}\right), \quad \tau < \tau_d \qquad (5)$$

where

S = rate of deposition, kg/sq m/sec

V_s = characteristic sediment settling velocity, m/sec

C = TSM concentration, kg/cu m

14. The three parameters that characterize the bed sediments τ_e , M , and τ_d were determined from the findings in Teeter (1987). Based upon Equation 1, τ_e was calculated to be 0.33 N/sq m or, for the accuracy of the flume tests, 0.3 N/sq m. Based on Equation 2, M was calculated to be 0.000082 kg/sq m/sec or, for the accuracy of the results, 0.0001 kg/sq m/sec. The flume test results reported in Teeter (1987) indicated a maximum value of τ_d of 0.12 N/sq m. In the range of shear stresses between τ_d and τ_e (for San Rafael Canal sediments, 0.12 N/sq m and 0.3 N/sq m, respectively), greatly reduced rates of erosion occur, which for the present study were considered to be negligible.

15. The sediment settling velocity V_s , used in Equation 5, is difficult to quantify. Often laboratory settling tests produce results that are lower than the actual V_s in the system, and generally V_s is proportional

to the TSM concentration. Settling tests at TSM concentrations in the range of those predicted in the San Rafael Canal were conducted on water samples from the WES 7-8 September 1988 intensive survey discussed earlier under the section, "Historical Data Analysis." The range of V_s measured was 0.00009-0.00019 m/sec. For somewhat higher TSM concentrations, a typical value of 0.0005 m/sec was reported in Teeter (1987). A value of 0.0002 m/sec was selected for use in this study as a compromise between the various results and the tendency of underdetermination of V_s by laboratory methods.

Dredging Records Analysis

16. The San Francisco District provided records of dredging in the San Rafael Canal and the San Rafael Channel in San Rafael Bay from the 1930's to the most recent dredging completed October 1987. Prior to 1942, the records provided inadequate information to determine whether the dredging occurred in the canal, the channel, or in both. After 1942, the dredging distribution could be reasonably reconstructed, and the results are provided in Table 1. The analysis of dredging records indicates an average monthly deposition of 0.0115 ft with a reasonable agreement of rates for the various dredging periods.

Table 1

Analysis of Dredging Records for San Rafael Canal

Date of Dredging	Amount Dredged cu yd	Estimated Months Between Dredging	Average Deposition Rate* ft/month
1947	42,500	60	0.0144
1954	58,507**	84	0.0138
1962	53,779**	96	0.0112
1969	53,435**	84	0.0128
Jan 1981	51,599	144	0.0072
Oct 1987	54,275	82	0.0135
		Weighted Average	0.0115

* Assumes an area dredged including side slope areas of 149,000 sq yd and uniform deposition along the canal.

** A total dredged quantity for both the San Rafael Canal and San Rafael Channel was provided. Based on limited data, the percentage of dredged material in the canal was assumed to be 22 percent of the total.

PART III: EVALUATION OF TIDAL BARRIER

17. The influences of the proposed tidal barrier on sedimentation and of sedimentation on the operation of the tidal barrier were analyzed since excessive deposition may prevent proper function of the barrier gate. These analyses were performed for the two possible barrier sites indicated in Figure 2. As an indication of the change in cross-sectional area resulting from the tidal barrier, predredge (early October 1987) and postdredge (late October and early November 1987) survey cross sections are provided in Figure 3 with the open tidal barrier superimposed upon the cross sections in its approximate location. In addition, a possible tidal barrier design is presented in Figure 4 to aid in the discussion of the possible impacts.

Evaluation Approach

18. The approach to evaluate the tidal barrier depended upon whether the sediments at the proposed site were derived from the San Rafael Creek or from the San Francisco Bay system. Since the proposed site is at the mouth of the San Rafael Canal, and the San Rafael basin has only a 7.1-square-mile drainage basin, initial indications were that the site was influenced more by bay sediments than by creek sediments. Similar conditions have been observed in other areas of San Francisco Bay, where sedimentation is determined more by movement of bay sediments than by direct fluvial input. For example, Einstein and Krone (1961) determined by observation and measurement that the excessive sedimentation in Mare Island Strait occurred predominantly in the summer as a result of the movement by currents of resuspended sediments in San Pablo Bay during the nearly daily high summer winds and resulting wave action, rather than during the winter when the majority of the sediments entered the estuary with the typical high riverine inflows of that time of year. Mare Island Strait is a deep, man-made channel on the extreme downstream end of the Napa River at Carquinez Strait.

19. In the San Rafael basin, the source of sedimentation in the Marina Vista Channel, which is a side channel off the north side of the extreme downstream end of the San Rafael Canal (Figure 2), was determined to be associated mostly with TSM arriving on the flood tide rather than with storm drain sediments from the city of San Rafael (Cheney and Krone 1987).

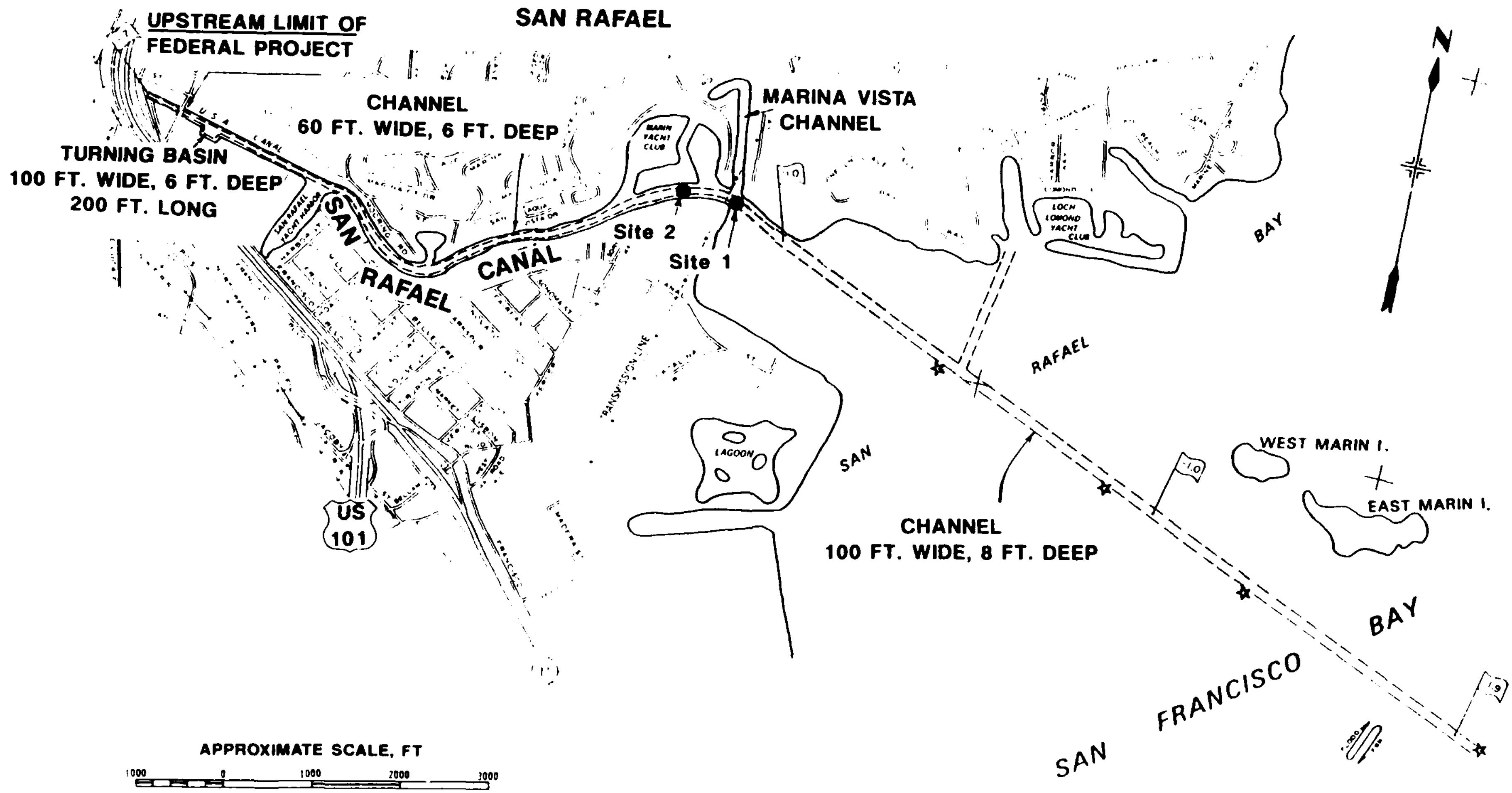
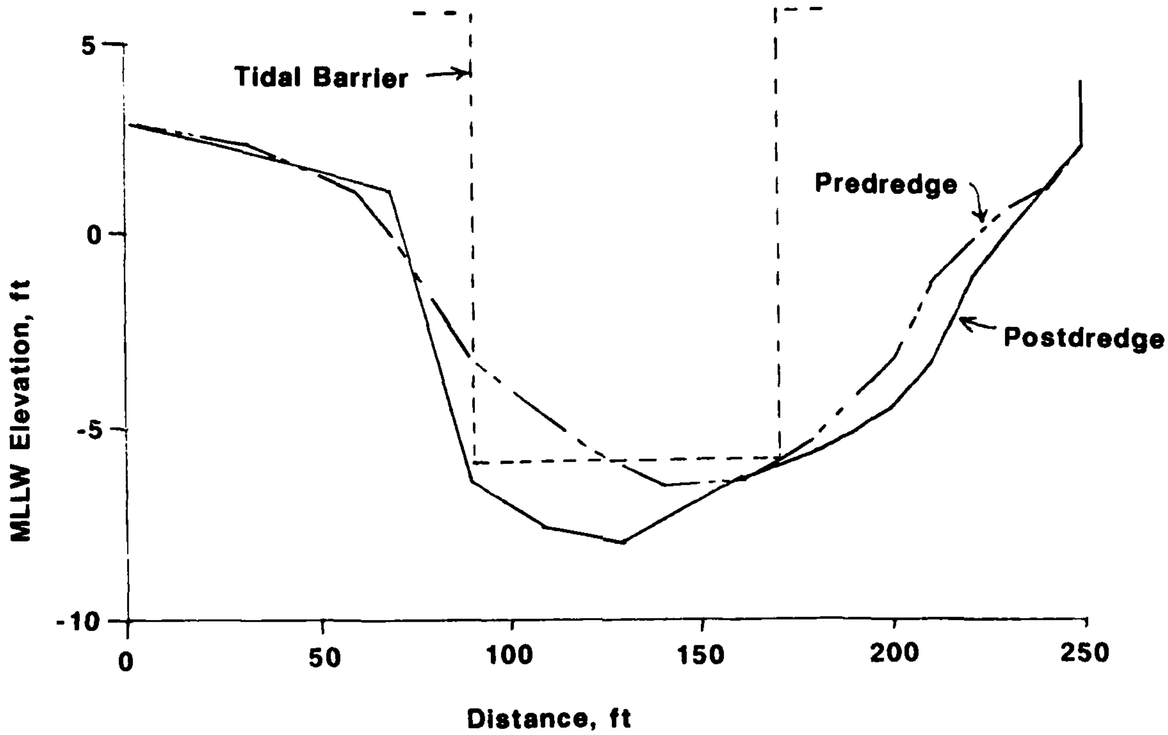
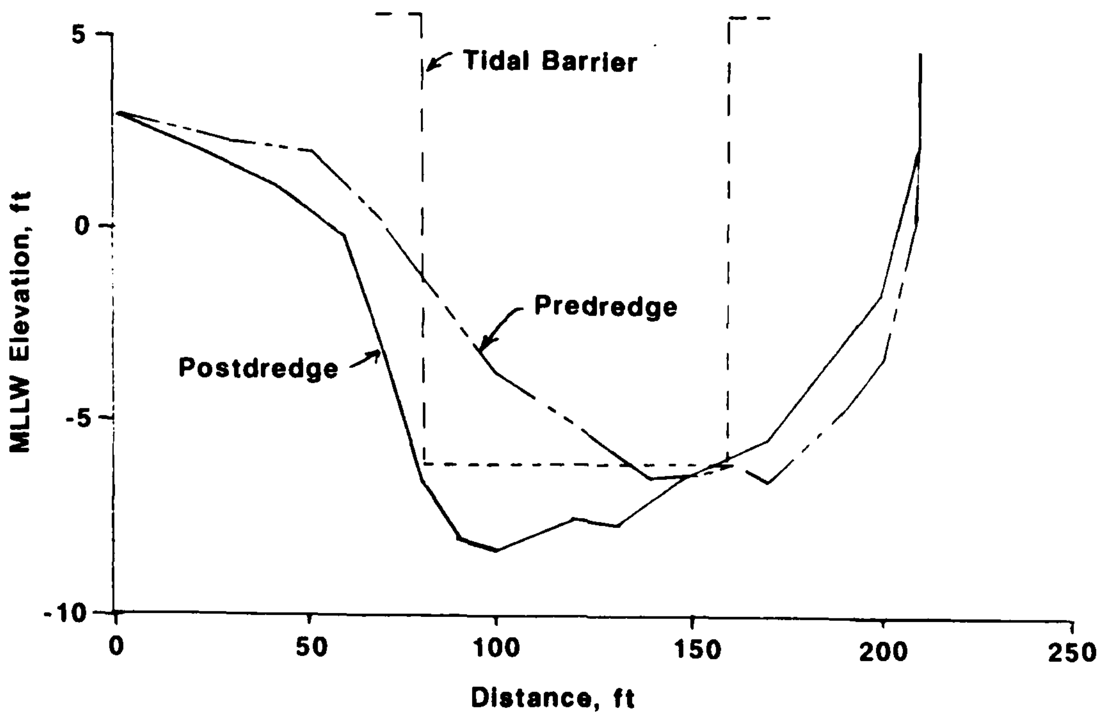


Figure 2. Alternative tidal barrier sites, San Rafael Canal



a. Site 1



b. Site 2

Figure 3. Cross sections at two alternative tidal barrier sites

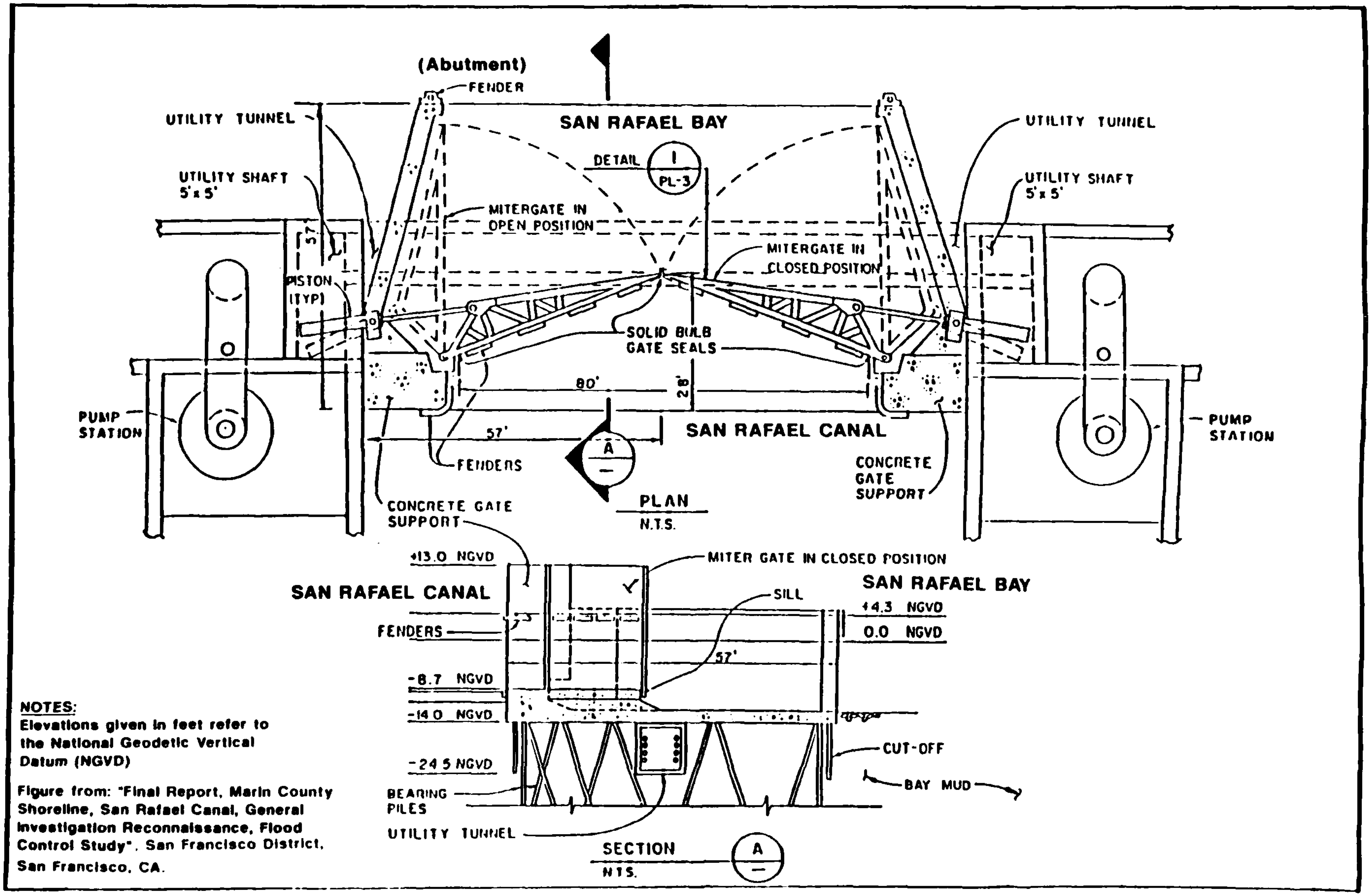


Figure 4. Preliminary design of San Rafael Canal tidal barrier and pumping station

20. The sediment cores from the 16 May 1989 field trip, which showed fine-grained, cohesive sediments without coarse sediment lenses, are indicative of sediments of estuarine origin. Attempts to obtain cores at the extreme upstream end of the San Rafael Canal were unsuccessful because the coarser bed material at this location prevented the sampler from penetrating into the sediments. This would indicate greater fluvial influences in the upstream end of the canal, which would be expected. The influence of fluvial sediments, however, would be expected to diminish rapidly in the downstream direction of the San Rafael Canal.

21. During freshwater flood events in San Rafael Creek, most of the coarse material would be expected to deposit upstream of the mouth of the San Rafael Canal. The high velocities of such an event would keep the fine-grained materials suspended until they reach San Rafael Bay. The small size of the San Rafael Creek basin and the episodic nature of runoff events that produce significant quantities of sediment support the minor role of fluvial sediments at the mouth of San Rafael Creek.

22. For these reasons, the analysis of erosion and deposition at the proposed tidal barrier sites will emphasize the estuary as the source of sediments.

Zero-Dimensional Model Analysis

23. Initial calculations indicated the complexity of the erosion-deposition conditions in the existing San Rafael Canal. Indications were that the lower canal, with and without the tidal barrier, was depositional at times and erosional at other times. In order to assess the long-term tendency of sedimentation in the lower canal and to determine any changes resulting from constructing a tidal barrier, a simple zero-dimensional numerical model was employed using the characteristics of sediments in the San Rafael Canal, the geometry of the canal, and the 1989 astronomical tide predictions for the site from the National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) (NOAA 1988). A detailed explanation of the model is presented in Appendix A. In summary, the zero-dimensional model is based upon the following:

a. The deposition and erosion at a specific cross section in the San Rafael Canal may be represented by the sedimentation to a unit area (zero-dimension) at the cross section.

b. Erosion and deposition of cohesive sediments at the site may be described by Equations 3 and 5 with bed shear determined by Equation 4, which are the equations employed for cohesive sediments in the two-dimensional finite-element model STUDH used in numerous WES sedimentation studies (Thomas and McAnally 1985).

c. The mean velocity through a cross section in the San Rafael Canal was assumed to be a function of the tidal prism represented by the tidally influenced area upstream of the cross section, the cross-sectional area, and the range of the tide (high water minus low water). Velocity direction is, of course, ebb or downstream on a falling tide and flood or upstream on a rising tide. Further, the tide was assumed to move as a standing wave, which is characteristic of many small basins. With a standing wave, slack water coincides with high and low water and maximum tidal velocity occurs near mean tide level. Finally, the velocity variation with time was assumed to behave in a sinusoidal manner.

d. Each rise or fall of the tide was divided into 10 equal time-steps, and the amount of erosion or deposition was determined for each of these time-steps.

e. An infinite depth of bed sediment was assumed to be available for erosion.

The model was operated for the astronomical tides for the year of 1989. With the semidiurnal tide in San Francisco Bay, two highs and two lows occur per 25-hour lunar day. The numerical model input parameters, which are based upon the data analysis part of this study, are listed in Table 2. The approximate average TSM concentration from historical data for San Francisco Bay near the proposed site (30 mg/ℓ) was used for the flood tide TSM concentration, and the approximate average of the water samples taken in the San Rafael Canal at high-water slack during the 16 May site visit (10 mg/ℓ) was used as the ebb tide concentration.

Zero-Dimensional Model Results

24. The model was operated for the following six conditions:

a. Predredge (early October 1987) cross section at site 1.

b. Postdredge (late October and early November 1987) cross section at site 1.

c. Tidal barrier at site 1.

d. Predredge cross section at site 2.

e. Postdredge cross section at site 2.

f. Tidal barrier at site 2.

Table 2
Zero-Dimensional Model Input Parameters

Parameter	Value
Manning's n roughness coefficient	0.018
τ_d	0.12 N/sq m
τ_e	0.3 N/sq m
M	0.0001 kg/sq m/sec
Ebb tide TSM concentration	10 mg/ℓ
Flood tide TSM concentration	30 mg/ℓ
V_s	0.0002 m/sec
Dry weight of bed sediments	500 g/ℓ
Tidal surface area above location 1	2.96×10^5 sq m
Tidal surface area above location 2	2.63×10^5 sq m
Cross-sectional areas	From Figure 3

The numerical model results are provided in Table 3.

25. Regarding the sedimentation processes in the immediate project vicinity, the last column in Table 3, net deposition, indicates the overall trend. These results should be viewed qualitatively rather than quantitatively, because of the degree of uncertainty associated with most parameters used in the model. Analyzed qualitatively, both proposed project locations have similar sedimentation tendencies. That is, existing channel conditions after dredging (postdredge) indicate a tendency toward deposition, the existing (predredge) channel is neutral with nearly balanced amounts of deposition and erosion, and the tidal barrier results in the potential for erosion. Since the tidal barrier is to be located on a concrete platform or pad, the erosion indicated by model results does not signify actual erosion, but rather the ability of tidal currents, especially during spring tides, to keep the pad free of substantial buildup of sediments.

26. A degree of validity of the numerical model results is indicated by the rough agreement of the assumed uniform deposition rates throughout the San Rafael Canal determined by investigating historic dredging records as reported in Table 1 and the results without tidal barrier in Table 3. From dredging records, a deposition rate of 0.14 ft/year is obtained, whereas model results range from -0.04 to 0.47 ft/year depending on location and predredge or postdredge channel cross section.

27. Interestingly, the numerical model indicates a tendency that as the existing cross-sectional area reduces due to shoaling, the velocities correspondingly increase, resulting in less deposition and substantially more erosion, until at the predredge conditions, deposition and erosion approximately balance. This does not mean that the entire length of the San Rafael Canal reaches this balance at the same amount of shoaling. Because the tidal prism (or upstream basin surface area) reduces in the upstream direction and the cross-sectional area remains nearly constant, reduced tidal velocities occur upstream in the canal. This implies that upstream even greater shoaling is required to reduce the cross section sufficiently to increase velocities to a point where erosion rates balance deposition.

28. Because there is a degree of uncertainty with many parameters used in the model, sensitivity tests were conducted. The influence of varying Manning's n, τ_d, τ_e, M, water column TSM concentration, V_s, and channel velocities U are provided in Table 4. Each parameter was varied

Table 3

Numerical Model Results of Sedimentation at Tidal Barrier Locations

Location	Velocity, fps		Maximum Bed Shear Stress N/sq m	Deposition		Erosion		Net Deposition ft/yr
	Average	Maximum		Time hr/yr	Amount ft/yr	Time hr/yr	Amount ft/yr	
				Site 1				
Predredge	0.44	1.93	1.03	6,859	0.51	472	0.54	-0.03
Postdredge	0.38	1.54	0.60	7,526	0.57	150	0.10	0.47
Tidal barrier	0.77	2.92	2.02	4,610	0.30	2,148	4.89	-4.59
				Site 2				
Predredge	0.44	1.91	1.02	6,801	0.51	493	0.55	-0.04
Postdredge	0.38	1.52	0.60	7,545	0.57	149	0.10	0.47
Tidal barrier	0.69	2.59	1.59	5,091	0.34	1,613	2.91	-2.57

independently with all other parameters held constant to the values in Table 2, and all model runs were operated with the same 1989 astronomical tide. The parameters were varied over a range related to the degree of confidence of the variable. Manning's n values for clay estuarine bottom surfaces are normally 0.015 to 0.020, so those extreme values were used. The values of τ_d and τ_e were varied ±50 percent. The values for M , TSM concentrations (both ebb and flood concentrations), and V_s were decreased 50 percent and increased 100 percent (halved and doubled). Tidal velocities were changed only ±20 percent, since they were based upon known cross sections, basin surface areas, and tidal ranges. These sensitivity results indicate net erosion at the tidal barrier for all parameter variations. However, the indicated net erosion varied from 0.46 to 10.9 ft. Therefore, with good degree of confidence, a tendency of scour or erosion is expected for sites 1 and 2, which will keep the concrete pad free of substantial buildup of sediments.

Influence of Tidal Barrier Abutments

29. Behind the abutments to the tidal barrier gates (Figure 4), areas protected from the main flow in the canal will be formed. These quiescent areas should produce conditions favorable to sedimentation. While this sedimentation will not interfere with gate operation, an increase in shoaling over existing rates could occur in these areas.

Tidal Range Evaluation

30. In order to estimate the influence of the tidal barrier on upstream conditions in the San Rafael Canal, an analytical approach for tidal inlets presented in WES (1984) was employed. The solution technique uses nomographs to determine a ratio of bay (San Rafael Canal) to driving tide (San Rafael Bay) tidal amplitudes based upon dimensionless friction and frequency coefficients and includes exit and entrance losses. The geometry of the inlet, in this case the tidal barrier, is included in the determination of the dimensionless coefficients. The technique assumes a sinusoidal tide, large inlet channel depth compared to tidal range, and vertical canal walls. These assumptions are valid, except the inlet channel depth is not extremely large

Table 4

Sensitivity Analysis of Parameters in the Zero-Dimensional Numerical Model

Parameter	Deposition		Erosion		Net Deposition
	Time hr	Amount ft	Time hr	Amount ft	ft
Base*	5,091	0.341	1,613	2.907	-2.566
n = 0.020	4,676	0.305	2,073	4.603	-4.298
n = 0.015	5,902	0.410	903	1.135	-0.725
τ_d = 0.06	3,687	0.233	1,613	2.906	-2.673
τ_d = 0.18	5,996	0.417	1,613	2.906	-2.489
τ_e = 0.15	5,091	0.341	3,161	11.243	-10.902
τ_e = 0.45	5,091	0.341	834	1.007	-0.666
M = 0.00005	5,091	0.341	1,613	1.453	-1.112
M = 0.0002	5,091	0.341	1,613	5.814	-5.473
0.5 × C**	5,091	0.171	1,613	2.907	-2.736
2 × C**	5,091	0.682	1,613	2.907	-2.225
V_s = 0.0001	5,091	0.171	1,613	2.907	-2.190
V_s = 0.0004	5,091	0.682	1,613	2.907	-2.225
0.8 × U	6,098	0.427	767	0.879	-0.452
1.2 × U	4,324	0.282	2,438	6.286	-6.004

* Base condition for sensitivity analysis is the tidal barrier at site 2.

** Ebb and flood concentrations both modified by the factor of either 0.5 or 2.

compared to the tidal range. The analysis was conducted using the tidal barrier as the inlet to evaluate the influence of the barrier on the tidal range in the San Rafael Canal. Because of the relatively low velocities and the short tidal barrier length, the impact of the barrier was analyzed to be totally insignificant. The ratio of San Rafael Canal tide to San Rafael Bay tide was determined to be 1.0 or identical in amplitude.

Freshwater Inflow Influence

31. Since the San Rafael Canal is the downstream portion of San Rafael Creek, which comprises a drainage basin of 7.1 square miles, runoff will drain into the canal. Because of the small drainage area relative to the size of the dredged San Rafael Canal, runoff to the canal normally would have insignificant impact on velocities. Particularly during the dry season of approximately May through November, the runoff would typically be insignificant. During relatively infrequent runoff events, sufficient inflow would occur to influence velocities at the proposed tidal barriers. The peak hydrographs provided by the San Francisco District were as follows:

$$Q_2 = 1{,}270 \text{ cfs}$$

$$Q_{10} = 2{,}700 \text{ cfs}$$

$$Q_{50} = 4{,}050 \text{ cfs}$$

$$Q_{100} = 4{,}600 \text{ cfs}$$

$$Q_{500} = 5{,}840 \text{ cfs}$$

where Q_n is the peak hydrograph flow at the mouth of the San Rafael Canal for an event with an exceedance interval of n years. (The Q_2 value was estimated from Q_{10} based upon analysis provided by Mathiesen.*)

32. The impact of any of these hydrographs on velocities in the

* Personal Communication from A. Mathiesen, May 1989, US Army Engineer District, San Francisco, San Francisco, CA.

San Rafael Canal at the proposed tidal barrier locations is dependent upon stage of the tide and tidal flow direction (ebb or flood). The 500-year event produces flows above 1,000 cfs at the mouth of the canal for only 12 hr, and the 10-year event produces flows above 1,000 cfs at the mouth of the canal for only 5 hr. If the peak portion of the hydrograph occurs during flood tidal flow, the two flows tend to counteract. If the peak flows occur during ebb tide, the result is an enhancement in velocities. During a typical spring tide, the peak tidal flow at the mouth of the canal is approximately 1,700 cfs, which is the approximate magnitude of the Q_2 and Q_{10} peak hydrographs.

33. Depending upon the timing of a large runoff event relative to the tide, the potential exists for enhanced, high velocities occurring for several hours. As an extreme, the peak hydrograph flow was added to the peak ebb tidal flow for a water surface of 1.0 ft mllw and the resulting bed shear stress τ was determined (Table 5). This simple analysis indicates the potential for high velocities and high shears in the natural channel, but even greater values occur with the tidal barrier in place. Very similar values would be determined for the tidal barrier at site 2. The consequence of τ values as high as those in Table 5 is the potential for rapid erosion, including the phenomenon of mass erosion in which layers of the bed muds are removed en masse rather than by individual particle erosion. Fortunately, these events resulting in high τ values would occur at an exceedance interval greater than those of the hydrograph exceedance interval alone, since the hydrograph peak would have to coincide with the time of maximum ebb flow for a spring tide. Also, the events would be of only a few hours' duration. However, the more extreme events, 50 years and greater, produce sufficient velocities to result in high τ values regardless of tidal currents.

34. Insufficient data exist on bay muds to quantitatively address erosion rates at the high τ values in Table 5. If Equation 3 is assumed valid for large τ values (a questionable assumption), the amount of erosion to a sediment with characteristics as used in the zero-dimensional model (Table 2), is 0.037 ft/hr for τ of 5 N/sq m, 0.076 ft/hr for τ of 10 N/sq m, and 0.155 ft/hr for τ of 20 N/sq m. At τ values in this range, Equation 3 may underpredict erosion rates. However, erosion could occur to deeper bed muds, which typically are significantly more erosion resistant than the surface muds sampled during the site visit.

Table 5

Maximum Bed Shear Stress from Combined Spring Tide Ebb Flow and Peak Hydrograph Events for Tidal Barrier Site 1*

Location	Maximum Ebb Tidal Velocity U_T fps	Q_2 Velocity U_2 fps	Q_{10} Velocity U_{10} fps	Q_{50} Velocity U_{50} fps	Q_{500} Velocity U_{500} fps	τ_2 $(U_T + U_2)$ N/sq m	τ_{10} $(U_T + U_{10})$ N/sq m	τ_{50} $(U_T + U_{50})$ N/sq m	τ_{500} $(U_T + U_{500})$ N/sq m
Predredge	1.93	1.40	2.98	4.47	6.45	2.8	6.0	10.2	17.6
Postdredge	1.54	1.17	2.49	3.73	5.38	1.8	3.9	6.7	11.5
Tidal barrier	2.92	2.24	4.75	7.13	10.28	6.2	13.8	23.6	40.8

* Velocities from peak hydrograph based upon water level at 1.0 ft mllw. The Q_{100} was not analyzed as the flow was not significantly greater than the Q_{50}.

PART IV: CONCLUSIONS

35. The influence of the proposed tidal barrier at the extreme downstream end of the San Rafael Canal (Figure 2) was evaluated at a feasibility level of study based upon historical data, limited field sampling, and a zero-dimensional numerical model. The findings and conclusions are discussed as follows.

36. Based upon the core samples taken at two alternative tidal barrier sites (Figure 2), the sediments were determined to be at least 80 percent clay and silts with approximately 10 percent fine sands. These samples, through the absence of a significant coarse material fraction, substantiated the intuitive evaluation that the sediments in the extreme downstream end of the San Rafael Canal in the area of the proposed tidal barrier originate from suspended sediments brought in on the tide from San Rafael Bay rather than from relatively infrequent rainfall runoff events in the San Rafael Creek basin.

37. A zero-dimensional numerical model was developed for cohesive soils to evaluate erosion and deposition at the two tidal barrier sites without the barrier in place for predicted astronomical tide data for the year of 1989. The results (Table 3) indicated an overall depositional to balanced pattern (erosion and deposition roughly equal) for the two sites without the tidal barrier. Deposition of slightly less than one-half foot per year was determined at both sites for the canal cross section based on postdredge measurements. With the increased velocities caused by the reduction to the canal cross section by shoaling, predredge data resulted in the prediction of very slight erosion (less than 0.05 ft/year) at both sites. These results are reasonably substantiated by evaluation of the dredging records from the 1930's to 1987, which indicate a deposition rate of 0.14 ft/year assuming uniform deposition in the canal.

38. The zero-dimensional model was also operated for astronomical tides for the year 1989 with the tidal barrier at both sites. A strong potential for erosion was determined with erosion of 4.6 ft/year at site 1 and 2.5 ft/year at site 2.

39. At both sites either with or without the tidal barrier, the tidal variations in canal velocities resulted in changing conditions with time. Even with the tidal barrier, the velocities were often sufficiently low to allow periods of deposition (Table 3). However, the frequency and duration of

velocities sufficient to erode bottom sediments increased sufficiently with the tidal barrier, which resulted in a net erosional environment.

40. The net erosional environment of the tidal barrier will act to keep the platform or base of the barrier scoured and free of significant sediment accumulation, which might otherwise interfere with gate closure. However, eddies and relatively quiescent areas behind the gates should result in increased shoaling behind the open tidal barrier gates compared with the present condition. In addition, the increased velocities leaving the tidal barrier will result in erosion to San Rafael Canal bottom sediments in the immediate areas to the east and west ends of the tidal barrier. In the extreme, this erosion could undermine the ends of the tidal barrier. The depth of erosion cannot be estimated without more information on the characteristics of deeper sediments in the canal. Erosion protection may be an advisable design consideration at the east and west ends of the tidal barrier.

41. Based upon an analytical tidal inlet method, the tidal barrier was determined to have no measurable impact on the tidal amplitude in the San Rafael Canal. Therefore, no measurable influences on the circulation, suspended sediment concentrations, and erosion and deposition patterns in the San Rafael Canal are expected, except in the immediate vicinity of the project.

42. Rainfall runoff events can have short-duration influences on the deposition and erosion characteristics of the San Rafael Canal. Because of the small drainage basin, the significant flood event hydrographs have durations measured in hours as opposed to days. The relatively infrequent hydrograph events (for example, exceedance intervals of 10 or more years) result in brief periods of high-velocity flow in the canal. These freshwater flood velocities are nearly doubled by the constriction of the tidal barrier. With the proper combining of peak hydrograph flows with spring tide maximum ebb flows, velocities in excess of 7 fps will occur for the 10-year exceedance interval event. High erosion rate potential will occur for the brief periods of these events in the immediate vicinity of the constriction.

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APPENDIX A: DESCRIPTION OF ZERO-DIMENSIONAL NUMERICAL MODEL

1. The zero-dimensional numerical model used in the analysis for the proposed tidal barrier in the lower San Rafael Canal was developed from a basis of existing principles and equations that describe tidal hydrodynamics and cohesive sediments. Through a zero-dimensional model, only a unit area of the San Rafael Canal or similarily behaving tidal basin is investigated as opposed to a one- or two-dimensional representation that would include the entire canal bottom surface area.

Cohesive Sediments

2. The equations describing erosion and deposition in this model are based on cohesive (clay) sediments. For erosion, the Ariathurai-Parthenaides equation given by Ariathurai, MacArthur, and Krone (1977)* was used:

$$E = M\left(\frac{\tau}{\tau_e} - 1\right) , \quad \tau > \tau_e \tag{A1}$$

where

E = rate of erosion

M = erosion rate constant

τ = actual bed shear stress

τ_e = bed shear stress above which erosion occurs

The Manning's shear stress equation is used to determine τ, in which

$$\tau = \frac{\rho g n^2}{h^{1/3}} U^2 \tag{A2}$$

where

ρ = water density

g = acceleration of gravity

* References cited in this appendix can be found in the References at the end of the main body of the report.

n = Manning's bottom roughness coefficient

h = water depth

U = vertically averaged current speed

3. For deposition, the equation of Krone (1962) is used:

$$S = V_s C \left(1 - \frac{\tau}{\tau_d}\right) , \quad \tau < \tau_d \tag{A3}$$

where

S = rate of deposition

V_s = characteristic sediment settling velocity

C = average total suspended matter (TSM) concentration in the water

τ_d = bed shear stress below which deposition occurs

In the model, C is assumed to be constant for a tidal flow direction. Therefore, a TSM value on the flood tide and on the ebb tide may be separately specified. The rationale is that the TSM concentration entering from San Rafael Bay on the flood tide may have a different value from the TSM concentration leaving San Rafael Canal on the ebb tide, especially if significant amounts of suspended sediments settle out in the canal system.

Tidal Hydrodynamics

4. The tidal hydrodynamics used in the model are based on the characteristic sinusoidal shape of tidal velocity and water level variations with time. Further, the tide was assumed to propogate as a standing wave in the San Rafael Canal, which is a valid assumption for a small enclosed basin. With a standing wave, high-water slack and high tide coincide as do low-water slack and low tide. Maximum tidal velocity occurs at mean water level, which is the time of maximum rate of water change. Therefore, temporal variations in water level may be described as:

$$D_t = \bar{D} + 0.5 \; R \sin (\phi_t) \tag{A4}$$

where

D_t = water-surface level at time t

$\bar{D}$ = 1/2(H + L) where H is the high water level and L is the low water level

R = tidal range (H - L)

ϕ_t = reference angle at time t

For a flood tide ϕ_t ranges from -0.5π to 0.5π, and for an ebb tide ϕ_t ranges from 0.5π to 1.5π. Temporal variations in velocity are described as

$$U_T = \frac{1.57\ \bar{Q} \sin(\phi_t)}{X_t} \qquad \text{(A5)}$$

where

U_T = cross-section mean velocity at time t

$\bar{Q}$ = average tidal flow $A \cdot R/\Delta T$ where A is the tidally influenced basin area upstream of the point of interest and ΔT is the time between high and low waters

X_t = cross-sectional area at water level D_t (Equation A4)

For a flood tide, ϕ_t ranges from 0 to π, and for ebb tide, from π to 2π. The high-water level H, the low-water level L, and time between high and low waters ΔT are all provided as input to the model. Typically H, L, and ΔT are provided as the values in the tide prediction tables obtained from National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) (NOAA 1988) in which the time and water level of high and low tide are provided for an entire year.

Time-Step

5. The model takes 10 equal time-steps per period from low to high water, or vice versa. The time-step is determined from the time of occurrence of each sequence of high and low waters. The model determines the amount of deposition and erosion and the duration of deposition and erosion for the entire simulation period, which may be numerous sequences of high and low waters.